TIME AND FREQUENCY ACTIVITIES AT THE CSIRO NATIONAL MEASUREMENT LABORATORY, SYDNEY, AUSTRALIA

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Abstract

The current activities of the Time and Frequency Section of the CSIRO National Measurement Laboratory are outlined. In addition to the usual responsibilities of a national timing laboratory, these activities include:
- ***Development of a trapped ion microwave frequency standard***
- ***Development of reliable, low cost GPS common-view time transfer systems***
- ***Two-way satellite time transfer***

INTRODUCTION

Australian Federal legislation requires the Commonwealth Scientific and Industrial Research Organisation (CSIRO) to maintain, or cause to be maintained, Australia's national standards for measurement of physical quantities. The National Measurement Laboratory (NML) discharges CSIRO's measurement standards responsibilities.

Consequently, the NML Time and Frequency section performs the following functions:
- Maintenance of the National Time Scale, UTC(AUS)
- Coordination of the input from clocks in Australia to the International Atomic Time Scale (TAI) maintained by BIPM

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- Maintenance of the National Frequency Standard (NFS)
- Maintenance of the international traceability of UTC(AUS) and the NFS
- Maintenance of the National Atomic Time Scale, TA(AUS)
- Maintenance of facilities for an in-house frequency and time interval calibration service.
- Maintenance of a frequency and time reference used as the basis of the frequency and time interval calibration service provided by the Melbourne Branch of NML
- Maintenance of the primary and backup Network Time Protocol (NTP) servers for Australia
- Monitoring, for timing purposes, of local TV-Sync signals in Sydney, Melbourne, and (from February 2000) Perth with respect to UTC(AUS)
- Monitoring, for timing and system integrity verification purposes in Sydney, Melbourne, and (from February 2000) Perth, signals from the Global Positioning System (GPS) satellite navigation system
- Monitoring, for timing and system integrity purposes, signals from the national HF time broadcast service, Radio VNG
- Processing of GPS timing data for Australian and international external customers for the purpose of time and frequency transfer.

Data generated by these services is disseminated in the form of:

- Test and calibration reports.
- Internet bulletin board (FTP)
- Internet timing signals (NTP)
- Bulletins and data files transmitted by electronic mail
- Bulletins sent by fax and conventional mail
- Participation in international campaigns, such as IGEX.

In addition, the NML Time and Frequency section undertakes a number of research projects:

- Development of a microwave frequency standard based on trapped ytterbium ions
- Development of low-cost GPS Common-View (GPSCV) time transfer systems to meet the needs of Australian and Asian customers
- Two-Way Satellite Time Transfer (TWSTT).

The content of this paper will be limited to an outline of recent progress in the above three research projects.

TRAPPED ION MICROWAVE FREQUENCY STANDARD

A microwave frequency standard based in the 12.6 GHz ground state hyperfine transition in $^{171}Yb^{+}$ ions confined in a linear Paul trap has been under development for several years [1,2].

The relevant energy levels of $^{171}Yb^{+}$ are shown in Figure 1. A 369.5 nm laser is used to prepare the ions in the F=0 ground state hyperfine level, and also to detect ions which have made the transition to the F=1 ground state level after interrogation with resonant 12.6 GHz microwave radiation.

The ions are confined in a linear Paul trap (Fig. 2). Helium at a pressure of 10^{-6} torr is introduced to the vacuum system to cool a cloud of about 10^{6} ions to a temperature of approximately 380 K. In this "buffer gas-cooled" mode of operation a frequency stability characterized by an Allan deviation $\sigma_y(\tau)=5\times10^{-14}\ \tau^{-1/2}$

(Fig. 3) has been demonstrated, with a calculated accuracy of ±2 parts in 10^{13} [1]. The greatest contribution to this uncertainty arises from the second-order Doppler shift due to the thermal motion of the ions.

More recently, attention has turned to the problem of improving the accuracy of the standard by laser-cooling the ions to sub-Kelvin temperatures (Fig. 4) in order to reduce the second-order Doppler shift. A major obstacle to building a frequency standard based on a laser-cooled ion cloud is the fact that during the Ramsey interrogation sequence, the 369.5 nm cooling laser must be blocked to avoid light shifts in the ground state hyperfine levels. RF heating of the ion cloud must be avoided during this period, which ideally would be several tens of seconds. Microwave Ramsey fringes on the cold ion cloud have been obtained with 10 s between the $\pi/2$ pulses (Fig. 5), and experiments have shown that sub-Kelvin temperatures can be maintained in the absence of the cooling laser for periods of 10 s or more. Measurements of the rate of, and factors contributing to, the RF heating of the cold ion cloud after blocking the cooling laser are in progress.

A preliminary error budget for the laser-cooled $^{171}Yb^{+}$ ion frequency standard, based on realistic extrapolations of present experimental results, is given in Table 1.

GPS COMMON-VIEW TIME TRANSFER SYSTEM DEVELOPMENT

There is a need within Australian commercial and government organizations for a time and frequency transfer system with the following features:

- Relatively low cost
- Upgradeability
- Capability of being operated remotely by NML, and consequently not requiring local staff to be familiar with GPSCV time transfer or the details of the operation of the system
- Data output in CCTF format
- Reliability.

Since we are not aware of a commercially available system with all of the above features, a system (Fig. 6) was developed in-house, based on the Motorola VP Oncore GPS engine and a PC running the LINUX operating system.

The principal advantages of the NML system over commercially available systems are that the components are all readily available and may be easily replaced or upgraded, and that the system is fully accessible via an Internet or modem link for data transfer, software maintenance and troubleshooting.

The Motorola company has indicated that the VP Oncore engine will not be sold after December 1999, and will be replaced by the M12 Oncore. Perusal of Motorola's literature on the M12 Oncore indicates that it will be fully compatible with the NML system after minor modifications to the NML software module, which interacts with the GPS engine.

Data from a zero-baseline comparison with an AOA TTR6 GPS time-transfer receiver sharing a common

timing reference are shown in Figure 7. The comparison exhibits RMS fluctuations of 8.6 ns, whereas a comparison over the same period between the original TTR6 and a second TTR6 exhibits RMS fluctuations of 3.7 ns, indicating that NML Motorola system is probably responsible for the excess fluctuations. The reason for these excess fluctuations is thought to be that the VP Oncore engine does not report the time over which the pseudo-range measurements are averaged, making the epoch corresponding to the center of the averaging period uncertain by a few ns. The M12 Oncore does report this information, so an improvement in performance over the VP Oncore due to this factor is hoped for.

The cause of the –58 ps/day drift evident in the data shown in Fig. 7 is unknown. Comparable drifts between NML's two AOA TTR6 receivers are also observed, so that it is not yet clear which receiver is responsible. Work continues on this issue.

NML Motorola-based systems are currently installed and operating at the following locations:

- NML, Sydney, Australia
- NML, Melbourne, Australia
- Measurement Standards Laboratory (MSL), Wellington, New Zealand
- Department of Fair Trading and Consumer Affairs, Suva, Fiji
- Scientific and Industrial Research Institute of Malaysia (SIRIM), Kuala Lumpur, Malaysia
- Industrial and Technical Development Institute (ITDI), Manila, Philippines
- National Institute for Metrology of Thailand (NIMT), Bangkok, Thailand
- Vietnamese Measurement Institute (VMI), Hanoi, Vietnam.

There is consequently a significant quantity of data available from these systems.

TWO-WAY SATELLITE TIME TRANSFER

NML is presently involved with two Two-Way Satellite Time Transfer (TWSTT) links. The details of these links are shown below:

Link 1:

Tx/Rx Band	C-Band
Earth stations	NML, Sydney, Australia and NIST, Ft. Collins, USA
Satellite	INTELSAT 701, 180°E
Tx power	10 W
Antenna	4.6 m
Modem	MITREX
Timing reference	H Maser (NML), High Perf. Cs (Ft. Collins)
Schedule	2 x 15 minute sessions per week
Regular operation began	July 1999

Link 2:

Tx/Rx Band	Ku-Band
Earth stations	NML, Sydney, Australia and CRL (Note 1), Tokyo, Japan
Satellite	INTELSAT 702, 177°E
Tx power	4 W
Antenna	2.2 m
Modem	ATLANTIS
Timing reference	H Maser (NML), High Perf. Cs (Ft. Collins)
Schedule	2 x 30 minute sessions per week
Regular operation began	March 1998 (Note 2)

Notes related to above tables:

(1) CRL = Communications Research Laboratory

(2) Operations suspended in May 1999 due to changes in satellite transponder assignment; scheduled to re-commence in February 2000.

The primary purpose of the TWSTT experiments is to compare the performance of GPS and TWSTT over very long (NML-NIST) and trans-equatorial (NML-CRL) baselines, over a period of several years. Results of these experiments will be published jointly with the other collaborating organizations.

REFERENCES

[1] P. T. H. Fisk, M. J. Sellars, M. A. Lawn, and C. Coles, "Accurate measurement of the 12.6 GHz 'clock' transition in trapped $^{171}Yb^{+}$ ions," *IEEE Trans. Ultrasonics, Ferroelectrics and Frequency Control*, vol. 44, pp. 344–354, 1997.

[2] P. T. H. Fisk, M. A. Lawn, and C. Coles, "Progress on the CSIRO trapped ytterbium ion clocks," in *Proc. Workshop on the Scientific Applications of Clocks in Space*, NASA Jet Propulsion Laboratory Publication 97-15, 1997, pp. 143–152.

FIGURES

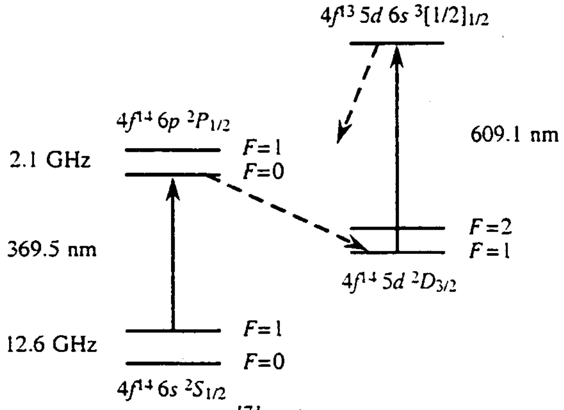

Figure 1: Partial energy level diagram of the $^{171}Yb^{+}$ ion. The 609.1 nm transition is used to drain the population accumulating in the metastable $^{2}D^{3/2}$ level, which would inhibit laser-cooling using the 369.5 nm resonance transition.

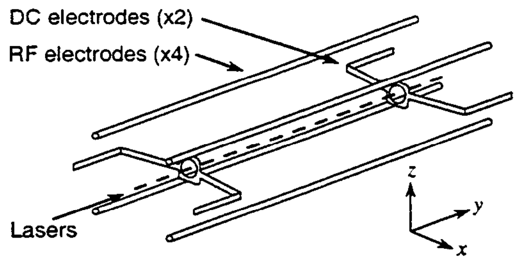

Figure 2: Electrode configuration of the linear Paul trap. For buffer gas-cooled operation the longitudinal electrodes are driven by an RF supply at approximately 300 V_{p-p} at 500 KHz, and the end electrodes are maintained at +10 V DC. In laser-cooled operation the values are 120 V_{p-p} at 750 KHz and 2 V respectively. The longitudinal electrodes are separated by 20 mm and the end electrodes are separated by 60 mm.

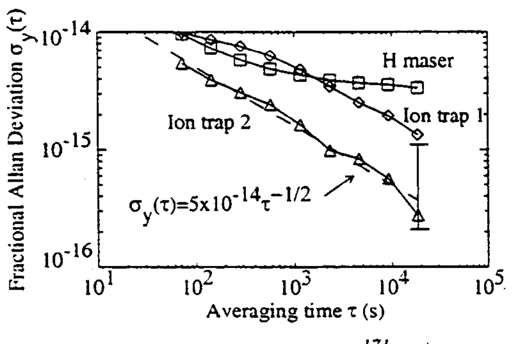

Figure 3: Stability performance of the two CSIRO trapped $^{171}Yb^{+}$ frequency standards operating in buffer gas-cooled mode, measured using the three-cornered-hat technique in conjunction with a H maser.

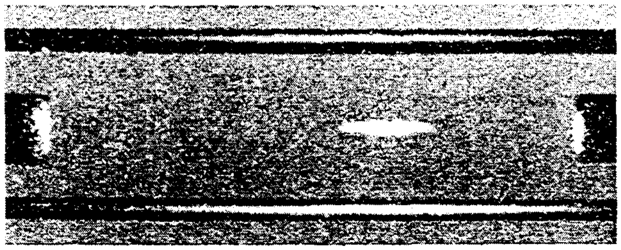

Figure 4: The laser-cooled ion cloud. The longitudinal RF electrodes are visible top and bottom (diameter 2.3 mm, separation 20 mm) and the DC end electrodes left and right (separation 60 mm). The temperature of the cloud is less than 200 mK.

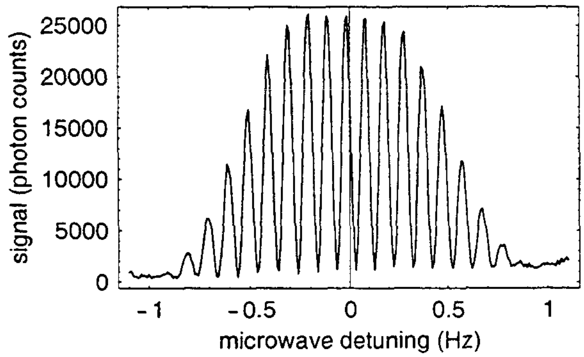

Figure 5: Ramsey pattern obtained on the 12.6 GHz $^{171}Yb^{+}$ clock transition with a $\pi/2$ pulse separation of 10 s, using the laser-cooled ion cloud shown in fig. 4. A background of 8000 counts due to laser scatter has been subtracted. The slight drift in the background is attributed to residual drift in the 369 nm beam intensity.

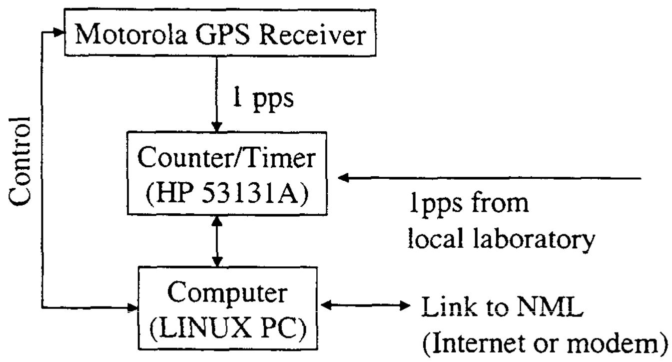

Figure 6: Schematic diagram of the NML GPSCV time-transfer system based on the Motorola VP Oncore GPS engine.

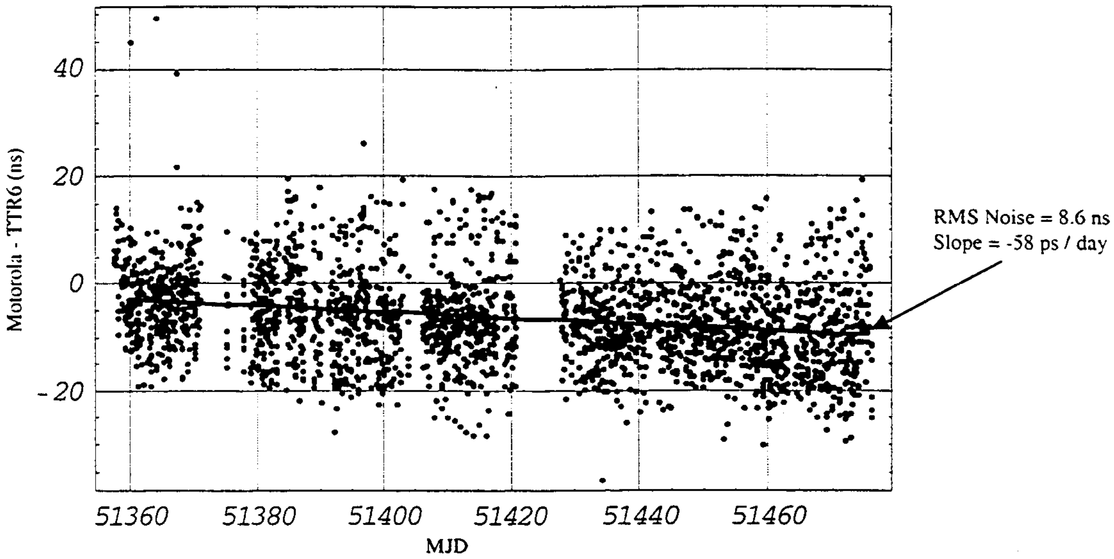

Figure 7: Zero-baseline comparison between the NML Motorola-based system and an AOA TTR6 system sharing a common timing reference.

Shift	**Magnitude (parts in 10^{15})**	**Uncertainty (parts in 10^{15})**
Second-order Doppler (micromotion)	5	2
Second-order Zeeman	300	2
AC Zeeman	< 2	1
Blackbody shift	20	1
Microwave non-ideality	1	1
	Total uncertainty	3.3

Table 1: Predicted frequency shifts and associated uncertainties for an ion cloud similar to that shown in Fig. 4, with radius 0.5 mm, length 10 mm, containing 10^4 ions at a temperature of less than 1 K. Possible additional frequency shifts and uncertainties resulting from residual background gas and magnetic inhomogeneity are not included.